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THE SHADOW WORLD

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Abstract

Recent attempts to construct a superstring theory that unifies all the interactions of nature including gravity in a finite, anomaly-free quantum theory have led to the speculation that there may exist another form of matter ('shadow matter') in the Universe, which only interacts with 'ordinary matter' (the quarks, leptons, etc. that we are familiar with) via gravity or gravitational-strength interactions. The existence of shadow matter would have a multitude of astrophysical and cosmological implications. We discuss some of them in this letter.

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Introduction

Superstring unified field theories (SUFTs) appear to offer the possibility of constructing a consistent quantum theory which unifies all the interactions including gravity.[1] In fact, it has been speculated that SUFTs are the only possibility for such a unification. Green and Schwarz[2] have shown that the only Type I superstring theories which are anomaly-free and finite are those based on the gauge groups SO_{32} or $E_8 \times E_8$ and have constructed a superstring theory based on SO_{32}. Recently, Gross, Harvey, Martinec, and Rohm[3] constructed a string theory based upon the gauge group $E_8 \times E_8$. The low energy limit of a string theory ($E^2 <<$ string tension $= m_{pl}^2$) is an ordinary quantum field theory (QFT). Since string theories are formulated in 10 dimensions, the effective QFT we see (and feel) is the low energy limit of a compactified string theory. It has been speculated that if the gauge group is $E_8 \times E_{8'}$, the $E_8 \leftrightarrow E_{8'}$ symmetry may persist even in the dimensionally-reduced theory.[3] If this is the case, then there would be two forms of matter, ordinary and shadow, which only interact via gravitational-strength interactions. In this letter we will consider possible implications of shadow matter in the Universe. It should be stressed that while our interest in shadow matter was stimulated by recent developments in superstring theories, our discussions apply to any theory which predicts the existence of 'shadow matter' (i.e., matter which only interacts gravitationally with ordinary matter). In fact, there are a variety of theories (e.g., those with so-called 'hidden' sectors[4]) which predict shadow matter.

Shadow Matter 'Exactly Mirrors' Ordinary Matter

We will consider several possible realizations for the shadow world. The first realization we will explore is that the shadow world exactly 'mirrors' the ordinary world. By 'exactly mirrors,' we mean that both the microphysics of the shadow world (symmetry breaking pattern, particle spectrum and masses, etc.) and macrophysics (photon temperatures, etc.) are identical. After the Planck epoch we can be sure that the interaction between shadow and ordinary matter is unimportant on the microscopic level since the rate for gravitational-strength interactions is much less than the expansion rate of the Universe. So although interactions among ordinary and shadow particles themselves will keep each separately in thermal equilibrium, the two worlds will not feel each other's presence on the microscopic level. If the two components are initially well-mixed, they will remain well-mixed until non-gravitational forces become important on macroscopic scales. In the standard cosmology this does not occur until the later stages of galaxy formation. During the early stages of structure formation ($t \gtrsim 10^{10}$ sec, $T \lesssim 10$ eV) small density inhomogeneities grow via the gravitational (or Jeans) instability. When the density contrast $\delta\rho/\rho$ begins to go non-linear (redshifts $\lesssim 30$), non-gravitational forces begin to play an increasingly important role--and of course, these forces will act separately on ordinary and shadow matter.

Structure formation which proceeds through the fragmentation of larger objects into smaller ones via hydrodynamical or thermodynamical instabilities will lead to the segregation of ordinary and shadow matter due to the random nature of the instabilities which act independently on the two components. In the hot dark matter or 'pancake' picture[5] large structures such as superclusters form and then fragment into galaxies via such instabilities, and so we would expect a segregation of ordinary and shadow matter on the scale of galaxies. In this case we expect to find galaxies which are predominantly ordinary matter, and others which are predominantly shadow matter together in clusters of galaxies. If galaxies do not form from the fragmentation of a larger object, as in the cold dark matter or hierarchical picture,[6] galaxies should contain equal amounts of ordinary and shadow material. However, objects that form via instabilities within galaxies, e.g., stars, will have ordinary/shadow segregation. Therefore, it is not unreasonable to expect that even if the disk of a galaxy contains equal amounts of ordinary and shadow matter, there may be local segregation of the two components (perhaps on scales larger than our solar system). We note that a roughly equal component of shadow matter in the disk of our galaxy would explain one of the several dark matter problems--that the gravitational mass of the disk (as inferred from dynamics) is about twice that of the material we can see or detect (stars, white dwarfs, gas, dust, etc.).[7] One might also expect some binary systems comprised of an ordinary star and a shadow star. Such a system would manifest itself as an isolated star with a periodic proper motion. In fact there are nearby stars ($d \lesssim 5$pc) which are suspected of having invisible companions.[8]

It is possible that our solar system formed from a nebulae containing ordinary and shadow matter (--although if the initial collapse of the protostellar nebulae were triggered by a shock wave, only the ordinary matter would have responded and collapsed). The shadow matter present would have formed into separate objects. However, with the exception of Nemesis, the death star,[9] we can be confident that there are no unseen planet-sized (or larger) objects in our solar system.

These considerations aside, what can one directly infer about the amount of shadow material in the earth or in the sun? Material in the earth is supported against gravity by atomic degeneracy pressure. The same would be true of shadow material in the earth. It would settle at the center of the earth (any initial motion relative to the center would be damped by tidal dissipation) and be distributed with a roughly constant density of the order of 10 g cm^{-3}. The mass of the earth derived from the motion of its many satellites,

$$M_{grav} = 4\pi\int(\rho_S + \rho)r^2\,dr = M_S + M,$$

and the mass derived based upon seismic determinations of ρ,

$$M_{seismic} = 4\pi\int\rho\, r^2\,dr = M,$$

are consistent at the 10% level.[10] (Here ρ and ρ_S refer to the density of matter and shadow matter respectively). This means that the amount of shadow material in the earth must be significantly less than that of ordinary material.

What about the sun? If the amount of shadow and ordinary material were equal, then the sun would be simultaneously a star and a shadow star, each burning its own kind of hydrogen to helium. However, as we shall see, the sun would appear very different indeed. If the shadow matter in the sun were distributed identically to the ordinary matter, then it is simple to show that the equations of stellar structure for each component are identical, and equivalent to the usual equations with G replaced by $2G_N$ and the usual mass variable M(r) (= mass interior to radial coordinate r) accounting for either the ordinary or shadow mass only (so that $M_{TOT}(r) = 2\,M(r)$). Using the standard stellar model (an n=3 polytrope);[11] it follows that the luminosity $\mathcal{L}$, rate of release of nuclear energy Q, central temperature T_c, and radius R are given by

$$\mathcal{L} \propto \mu^7 (GM)^5 G^2 T_c^{1/2}$$

$$Q \propto \mu^{-3} (GM)^{-1} G^{-2} T_c^{p+3}$$

$$T_c \propto \mu^{10/(p+2.5)} (GM)^{6/(p+2.5)} G^{4/(p+2.5)}$$

$$R \propto \mu (GM) T_c^{-1}$$

where μ is the average molecular weight per particle, and $p \approx 4$ accounts for the approximate temperature dependence of the nuclear reactions responsible for energy generation in the sun. [Note, the central temperature is determined by the equilibrium condition: $\mathcal{L} = Q$.]

A solar mass star composed of equal quantities of ordinary and shadow matter corresponds to: $G = 2G_N$ and $M = M_S = M_\odot/2$. The standard stellar model of such an object predicts: $\mathcal{L} \simeq 5\mathcal{L}_o$, $T_c \simeq 1.5T_{co}$, and $R \simeq 0.65R_o$, where 'subscript zero' indicates the value of that quantity for a standard solar mass star ($M = M_\odot$, $G = G_N$) with the <u>same</u> chemical composition. Such a star would be easily distinguishable from 'our sun' by its luminosity, size, and solar neutrino flux (the flux of ^8B neutrinos detected by the Davis experiment is very temperature-dependent, neutrino flux $\propto T_c{}^q$, $q \simeq 13$ [12]). Although $\mathcal{L}$, T_c and R are all dependent upon the chemical composition, it is not possible to adjust μ to obtain a model which resembles 'our sun'. Ulrich,[13] and Mikkelsen and Newman[13] have constructed numerical models of the sun where they fixed GM, but allowed G to differ from G_N; from such models they concluded that G/G_N must be in the range 0.6-1.5. In passing we note that the Chandrasekhar mass for a star containing equal amounts of ordinary and shadow matter is smaller than the usual value by a factor of $\sqrt{2}$.

If there is only a small amount of shadow matter in the sun ($M_S \ll M_\odot$) the analysis is quite different. In this case the shadow material will sit at the center of the sun and will be supported by shadow electron degeneracy pressure. In the limit $M_S \ll M_\odot$ and $\rho_S \ll \rho$ it is simple to compute the size and central density of the shadow object sitting in the sun's core:

$$R_S \simeq 0.2R_\odot(M_S/M_\odot)^{1/6},$$

$$\rho_S \simeq 2000 \text{ g cm}^{-3} (M_S/M_\odot)^{1/2}.$$

If as before the shadow matter were distributed as the ordinary matter, then we could use the formulae presented above with GM fixed and $G \rightarrow G_N(1 + M_S/M_\odot)$ to compute the effect on the sun. Because in this case the shadow material is more centrally concentrated its effect should be even larger. Since all the interesting physics is going on in the core ($r \lesssim 0.1R_\odot$) where the shadow material is located, a reasonable approximation is to take GM fixed and $G \rightarrow G_N(1 + \rho_S/\rho_c) \simeq G_N(1 + 10(M_S/M_\odot)^{1/2})$. In this approximation the central temperature would rise by an amount:

$$\delta T_c/T_c \simeq 6(M_S/M_\odot)^{1/2}.$$

As mentioned earlier, the most sensitive indicator of the central temperature of the sun is the solar flux of ^{8}B neutrinos. Taking the flux to vary as T_c^{13} and insisting that the predicted rate not triple, say, implies that $\delta T_c/T_c \lesssim 0.09$ or

$$M_S/M_\odot \lesssim 0.001.$$

To conclude the discussion of shadow matter in the solar neighborhood we can say that, save the possibility that Nemesis is a shadow object, there can be little shadow matter in the solar system. As we mentioned earlier, since it is reasonable to believe that the shadow matter and ordinary matter could easily be segregated within the galaxy on scales the size of the solar system, this observation does not preclude the existence of an exactly mirror shadow world.

Primordial Nucleosynthesis

Now let's turn to the early Universe. The yields of big bang nucleosynthesis depend sensitively upon the expansion rate of the Universe one second after the bang, when the temperature was about 1 MeV.[14] The expansion rate of the Universe at nucleosynthesis is related to the total energy density, $\rho_T = \rho + \rho_S$, by

$$\dot{R}/R = [(8\pi G/3)(\rho + \rho_S)]^{1/2}.$$

During this early epoch the Universe is radiation-dominated, with $\rho = g_*(\pi^2/30)T^4$, where g_* counts the effective number of degrees of freedom of particles with mass less than T:

$$g_* = \sum_{\text{bosons}} g_B + 7/8 \sum_{\text{fermions}} g_F.$$

The addition of shadow matter at a temperature T_S (= temperature of the shadow world) results in an effective g_* at the time of nucleosynthesis

$$\rho_T = g_{eff}(\pi^2/30)T^4$$

$$g_{eff} = g_* + g_{*S}(T_S/T)^4$$

where g_{*S} counts the effective number of degrees of freedom in the shadow world. Increasing the expansion rate results in the production of more ^{4}He: $\Delta Y_p \approx 0.19 \log_{10}(1+\Delta g/g_{eff})$.[14] Here Y_p is the mass fraction of ^{4}He synthesized, and Δg is the change in g_{eff}.

Taking into account observational data (which strongly suggest $Y_p \lesssim 0.25$), uncertainty in the neutron half life, and uncertainty in the calculated abundances, Yang etal.[15] conclude that unless the number of light ($\lesssim$ few MeV) neutrino species $N_\nu \lesssim 4$, ^{4}He will be overproduced. In fact if Y_p were known to be ≤ 0.250 (i.e., to three significant figures), $N_\nu = 4$ is not quite allowed. Note that $N_\nu = 4$ corresponds to $g_* = 12.5$.

The limit on the number of neutrinos is really a limit on the total effective number of degrees of freedom, g_{eff}. For purposes of our discussions, we will be conservative and take the primordial nucleosynthesis limit to g_{eff} to two significant figures:

$$g_{eff} \lesssim 13.0.$$

For the exact mirror shadow world, $g_{eff} = 25(N_\nu = 4)$, $21.5(N_\nu = 3)$, or $18(N_\nu = 2)$. Thus, big bang nucleosynthesis rules out exact mirror symmetry since we know that at least two of the neutrino species are light.

Macroscopic Asymmetry/Microscopic Symmetry

Having ruled out the possibility of an exact mirror shadow world, brings us to discuss the possibility of a macroscopic asymmetry between the two worlds with identical microphysics. A quantity which specifies the macroscopic asymmetry in a very useful way is the ratio of the entropies per comoving volume Υ:

$$\Upsilon \equiv \frac{s_S R^3}{s\ R^3} = \frac{g_{*S}(T_S)}{g_*(T)} \quad \frac{T_S{}^3}{T^3}$$

where s (s_S) is the ordinary (shadow) entropy density and R is the cosmic scale factor. In the absence of entropy production in either world Υ remains constant. For the scenario at hand (identical microphysics) $g_* = g_{*S}$ so that Υ, the ratio of the entropy of the shadow world to our world, is just $r^3 = (T_S/T)^3$. Lacking a detailed understanding of how the compactification from d=10 to d=4 took place, <u>a priori</u> we do not know what value of Υ to expect, although 1 seems like a natural value.

For the case of identical microphysics ($g_* = g_{*S}$), the primordial nucleosynthesis constraint (i.e., $g_{eff} \lesssim 13.0$) implies that

$$\Upsilon \leq \begin{cases} 0.55 & N_\nu = 2 \\ 0.31 & N_\nu = 3 \\ 0.09 & N_\nu = 4 \end{cases} \quad .$$

Assuming that the ordinary and shadow baryon-to-entropy ratios are identical, this implies that ordinary baryons must outnumber shadow baryons:

$$n_B/n_{BS} \geq \begin{cases} 1.8 & N_\nu = 2 \\ 2.0 & N_\nu = 3 \\ 11.0 & N_\nu = 4 \end{cases} .$$

If $T_S \neq T$ the shadow baryon asymmetry may differ from the normal baryon asymmetry even though the microphysics is the same for both worlds. In baryogenesis scenarios the baryon-to-entropy ratio, B, is a function of $K = (\Gamma_I/H)_{T=M_X}$, where Γ_I is the microphysical interaction rate of some baryon number violating boson X, M_X is its mass, and H is the expansion rate of the Universe ($\simeq \rho_T^{1/2} m_{pl}^{-1}$).[16] If the shadow and ordinary microphysics are the same, and the Universe is radiation-dominated at baryogenesis ($\rho_T \propto T^4 + T_S^4$), the relevant values of K for ordinary and shadow baryogenesis (K and K_S) will be proportional to

$$K \propto \frac{m_{pl}}{M_X[1+r^4]^{1/2}} \quad ,$$

$$K_S \propto \frac{m_{pl}}{M_X[1+r^{-4}]^{1/2}} \quad ,$$

where as before $r = T_S/T$. If no entropy is created between baryogenesis and nucleosynthesis, r must be less than 1 and so $K_S < K$. The baryon asymmetry decreases with increasing K,[16] so the ordinary baryon asymmetry must be less than or equal to the shadow baryon asymmetry.

For $K \lesssim 1$, the baryon asymmetry is independent of K and thus would be the same for ordinary and shadow matter. For $K \gtrsim 1$, the baryon-to-entropy ratio is roughly proportional to K^{-1}, and the ratio of shadow to ordinary baryon numbers is given by

$$
\begin{aligned}
B_S/B &\simeq [1 + r^{-4}]^{1/2}/[1 + r^4]^{1/2} \\
&\simeq r^{-2} \qquad (r < 1).
\end{aligned}
$$

The number density of shadow baryons, n_{BS}, is related to the number density of ordinary baryons n_B by

$$
\begin{aligned}
\frac{n_{BS}}{n_B} &= \frac{B_S}{B} \; \frac{T_S{}^3}{T} \\
&= r^3 \qquad (K, K_S < 1) \\
&= r \qquad (K, K_S > 1).
\end{aligned}
$$

Since we know that $r < 1$ from nucleosynthesis, it is difficult to imagine a scenario where shadow baryons dominate ordinary baryons (by number).

We have shown that Υ must be less than one. Even if Υ were $\gtrsim 1$ initially it is possible that it was reduced exponentially by inflation.[17] If the two worlds are microscopically identical we would expect inflation to occur in both sectors -- but not necessarily simultaneously. Remember inflation involves a random event -- the nucleation of a bubble or the formation of a fluctuation region. At the beginning of inflation the Universe is in a false vacuum state for both worlds. A bubble will nucleate (or a fluctuation region will form) for one of the worlds first, say the shadow world. As that bubble grows exponentially in physical size (i.e., inflates), both T and T_S decrease exponentially and Υ remains constant. When the shadow vacuum energy is converted into radiation the shadow temperature will rise to T_{RH}, and Υ increases dramatically. The Universe, however, is still inflating, driven by the vacuum energy of the ordinary sector. Eventually, a bubble (or fluctuation region) forms for the ordinary world, within the shadow bubble. During this second phase of inflation, the new bubble grows exponentially in size, while both T and T_S decrease exponentially. When the vacuum energy of the ordinary world is converted into radiation, the temperature of the ordinary world rises to T_{RH}, a temperature which is exponentially larger than the temperature of the shadow world. Thus Υ has been reduced to an exponentially small value by 'double-bubble inflation'. If 'double-bubble inflation' did occur, then the shadow world is exponentially uninteresting. We note that if inflation occurs in the 10-dimensional phase, or during the compactification transition, inflation and $\Upsilon=1$ are not necessarily incompatible.

Asymmetric Microphysics

Now let's consider the possibility that the symmetry between the ordinary world and the shadow world is broken microscopically. A scenario has recently been discussed where the 10-dimensional string theory is compactified on a 6-dimensional, Ricci-flat Calabi-Yau

Manifold to the 4-dimensional theory $E_8 \times E_6$.[18] In this scheme E_6 is the gauge group of the ordinary world and E_8 is the gauge group of the shadow world.

If the microphysics of the shadow world is not identical to that of the ordinary world there are additional means (other than inflation) for changing the entropy ratio γ. They include the very out-of-equilibrium decay of a massive particle species[19-21], or a phase transition that is only mildly inflationary (e.g. an entropy increase of less than 10^6 during the $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$ transition).

In the case of asymmetric microphysics the very stringent nucleosynthesis bound can be evaded even if the two worlds have identical initial entropies. Recall that nucleosynthesis bounds g_{eff} to be $\leq$ 13. If we assume that the expansion of the Universe has been isentropic since the beginning, then g_{eff} is given by

$$g_{eff} = g_*[1+\gamma^{4/3}(g_*/g_{*S})_{BBN}^{1/3}],$$

where BBN denotes the value at big bang nucleosynthesis when $T \simeq O(\text{MeV})$. The primordial nucleosynthesis constraint $g_{eff} \leq 13.0$ results in a lower bound on $(g_{*S})_{BBN}$

$$(g_{*S})_{BBN} \gtrsim \gamma^4 \qquad \begin{cases} 103 & N_\nu = 2 \\ 1172 & N_\nu = 3 \\ 1.95\times10^5 & N_4 = 4 \end{cases}$$

If the E_8 of the shadow world remains unbroken and the representational content of the shadow world is, as has been suggested, a single N=1 gauge supermultiplet, then $g_{*S} = 930$. Of course if Υ is less than one (macroscopic asymmetry), the constraint could also be satisfied.

Before going on we should mention that if one writes the constraint in terms of the initial temperature ratio $r_i = (T_S/T)_i$ instead of the entropy ratio Υ, the constraint becomes an <u>upper</u> bound on g_{*S}:

$$(g_{*S})_i (g_{*S})_{BBN}^{-1/4} \leq (g_*)_i r_i^{-3} (13 - g_{*BBN})^{3/4} g_{*BBN}^{-1}$$

where 'subscript i' denotes the value of a quantity at the initial epoch and 'subscript BBN' the value at the epoch of primordial nucleosynthesis ($T \simeq 1$ MeV). If $(g_{*S})_i = (g_{*S})_{BBN}$, then the constraint becomes

$$(g_{*S})_{BBN} \leq (g_*)_i^{4/3} r_i^{-4} \begin{cases} .213 & N_\nu = 2 \\ .095 & N_\nu = 3 \\ .017 & N_\nu = 4 \end{cases}$$

<u>Massive Shadow States</u>

If the shadow group (or some non-Abelian subgroup) remains unbroken, some coupling will become strong at an energy scale Λ_S (unless the β-function vanishes), and the theory may become confining. If the theory is confining, the typical mass of the physical states would be Λ_S, with the possible exception of massless Nambu-Goldstone particles. In this section we will consider the various cosmological implications of massive shadow states. Although our motivation for consideration of these states is the possibility that the shadow sector is confining, our arguments do not depend upon the origin of the massive shadow states.

We first consider the possibility that the massive confined states decay. This is possible only if all conserved quantum numbers carried by the massive states are carried by the massless decay products. If there are such massless shadow states, the decay width for the massive states should be $\Gamma_S \simeq \Lambda_S$. If there are no massless shadow states, the massive ones can only decay via gravitational-strength interactions to gravitons or ordinary matter. Here, we will only treat the graviton case for which the decay width is $\Gamma_S = \Lambda_S(\Lambda_S/m_{pl})^n$, where n=4 for a two body bound state which annihilates into gravitons. If $\Gamma_S \simeq \Lambda_S$, the massive states decay before they become dynamically important. If however, the states must decay by gravitational-strength interactions to gravitons the lifetime may be sufficiently long that the massive states dominate the energy density of the Universe before they decay. When they decay into gravitons, the gravitons will have an energy density $\rho_g \simeq \Lambda_S T_{SD}^3$, where T_{SD}^3 is the number density of the massive shadow particles at decay. The gravitons will act as shadow matter during nucleosynthesis, since they will not thermalize with ordinary matter. At the decay epoch ordinary matter has an energy density $\rho \simeq T_{SD}^4 r_i^{-4}$. After decay and through nucleosynthesis ρ_g/ρ will remain constant. Primordial nucleosynthesis requires that ρ_g/ρ be less than 0.2 (for N_ν = 3); using this we can obtain a bound on Λ_S. The massive particles decay when the expansion rate of the Universe (inverse of the age of the Universe) equals their decay width (inverse of the lifetime). Setting H = $\rho^{1/2}\, m_{pl}^{-1} \simeq T_{SD}^2 r^{-2} m_{pl}^{-1}$ equal to $\Gamma_S \simeq \Lambda_S(\Lambda_S/m_{pl})^n$, gives ρ_g/ρ = $r^4 \Lambda_S/T_{SD} = r_i^3(\Lambda_S/m_{pl})^{(1-n)/2}$. The limit that follows from $\rho_g/\rho < 0.2$ is:

$$\Lambda_S \gtrsim (5\, r_i{}^3)^{2/(n-1)}\, m_{pl} \quad ,$$

$$\Lambda_S \gtrsim 3r_i^2 m_{pl} \qquad (n = 4).$$

If $r_i = O(1)$, the theory would have to confine at a scale $\Lambda_S \approx m_{pl}$ in order that the massive states be able to decay early enough.

Before leaving the question of decay we would like to comment on the possibility that the massive states decay into ordinary matter. In that case, the decays can 'heat up' the ordinary matter and increase the ordinary entropy,[21] and constraints follow from nucleosynthesis[21] and baryogenesis.[19,20]

If the massive shadow states cannot decay, they may disappear via annihilation. If there are massless shadow states the annihilation cross section will be $\sigma_A \simeq \Lambda_S^{-2}$. If there are no massless shadow states, annihilation must be via gravitational-strength interactions into gravitons (or possibly ordinary matter) with $\sigma_A \simeq \Lambda_S^{-2}\ (\Lambda_S/m_{pl})^n$, where for two-body annihilation via graviton exchange n=4. If $\sigma_A \simeq \Lambda_S^{-2}$, the relic abundance of massive particles that survive annihilation has been calculated by Wolfram[22] and Steigman.[23] The relic particles would today contribute a fraction of the critical density

$$\Omega_S \simeq 10^{29}\gamma(\Lambda_S/m_{pl})^2 \qquad (\sigma_A = \Lambda_S^{-2}),$$

where due to the inherent uncertainties we have ignored factors of g_*, g_{*S}, a logarithmic correction and the dependence on the Hubble parameter. The fact that $\Omega_S \lesssim O(1)$ implies

$$(\Lambda_S/m_{pl}) \leq 3\times10^{-15}\gamma^{-1/2} \qquad (\sigma_A = \Lambda_S{}^{-2}).$$

If the annihilation is into gravitons, then the annihilation rate is always much less than the expansion rate, and the massive states do not annihilate. In this case the present density of the massive states will be

$$\Omega_S = 10^{27}\gamma(\Lambda_S/m_{pl}). \qquad [\sigma_A = \Lambda_S^{-2}(\Lambda_S/m_{pl})^4]$$

Requiring $\Omega_S \lesssim O(1)$ implies that

$$\Lambda_S/m_{pl} \lesssim 10^{-27}\gamma^{-1}.$$

To summarize the results of this section, if the decay of the massive confined states cannot occur through strong shadow forces, then Λ_S/m_{pl} must be $\geq 3r_i^2$. If this inequality is not satisfied, or if some quantum number forbids decay, then the massive states must annihilate, which requires $\Lambda_S/m_{pl} \lesssim 3\times10^{-15}\gamma^{-1/2}$ if there are massless confined states, or $\Lambda_S/m_{pl} \lesssim 10^{-27}\gamma^{-1}$ if there are no massless confined states. If one of the annihilation bounds is saturated, 'shadow relics' would be the dark matter and provide $\Omega_{TOT} = 1.0$.

In conclusion, the effect of shadow matter is hard to detect in everyday life - the reader could be living in the middle of a shadow mountain or at the bottom of a shadow ocean. But it would have many effects in the early and in the contemporary Universe. We have shown that an exact mirror Universe is ruled out by primordial nucleosynthesis. Our constraints, however, do not rule out the possibility that shadow matter plays an interesting role in the evolution of the Universe.

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